Structural and Geotechnical Analysis of the Brihadeeswara Temple Foundation

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***Abstract*— Brihadeeshwara temple (or the big temple) of Tanjavur in Tamil Nadu celebrated 1000 years of existence recently. It was built by the king Raja Chola I. The temple complex is one of the UNESCO world heritage sites and stands tall as a spell-binding example of intricate and unparallel Indian architecture. The inner sanctum or Vimana of the main temple is 66 m high and is made up of granite stone housing the Siva deity in a hollow Garbhagriha. This tower is topped by a granite capstone weighing about 80 tons. It is believed that the massive capstone is brought from a farther distance from the temple complex. The nearly impossible task of placing this stone on the top of the sanctum appears to be a geotechnical challenge during the temple construction. Recent speculations suggest the use of elephants for rolling the spherical, massive stone on the sloped ramps or helical sand slopes around the finished Vimana percent.**

***Index Terms*— Soil–Structure Interaction, Settlement Analysis, Stress Distribution, Load Transfer Mechanism, Structural Stability, Ancient Engineering**

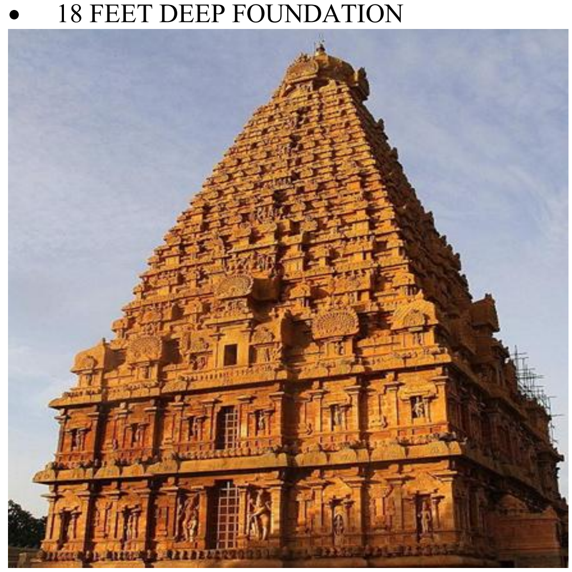
I. INTRODUCTION

India is blessed with countless historic structures showcasing incredible craftsmanship and architectural beauty. The Ajanta and Ellora caves of Aurangabad, Taj Mahal of Agra, Sun Temple of Konark, the Vijayanagara remains of Hampi, etc. are only a few examples amongst the numerous golden feathers in the crown of Indian engineering and construction raised centuries ago. Ruled by the powerful kings of Pallavas (600-900 AD), Cholas (900-1150AD), Pandyas (1150-1350 AD), Vijayanagaras (1350-1565 AD) and Nayakas (1600-1750 AD), (Deva,1995) south India is dotted with many great temples which are famous not only for their exquisite sculptures but also for the unbelievable proportions. Methods adopted by them for raising such extreme buildings are unknown to the present generation of engineers and therefore hold a lot of fascination.

The Brihadeeshwara Temple also known as the Peruvudaiyar Kovil, situated in the Tanjavur district of Tamil Nadu is a fine example of Dravidian architecture and represents the Chola empire ideology. The temple was completed in 1010 AD, under the reign of the king Raja Raja Chola I (985 AD-1014AD). It is a UNESCO World Heritage Site as well (Mukherjee, 2001). The main architect and engineer, Kunjara Mallan Raja Raja Perunthachan, constructed the temple as per the Vaastu Shastra and Agamas. The sanctum sanctorum of the temple enshrines a 3.66 m high Shiva Linga. (Michell., 1989). The temple Vimana is a hollow, pyramidal structure, 66 m tall and is one of the tallest temple towers on the earth. Made out of at least 1,30,000 tons of granite, (Srividhya, 2014) the temple complex has withstood a number of earthquakes and furies of nature.

STRUCTURAL DETAILES:

- 216 FEET TEMPLE TOWER (66) METERS
- 12 FEET HIGH VIGRAH (SHIVA IDOL)
- 18 FEET DEEP FOUNDATION



TEMPLE TOWER (VIMANA GOPURAM)

Along with other feats associated with the temple construction, the placement of the single granite capstone or cupola weighing 80 tons atop the Vimana of the temple.

II. METHODOLOGY

Granite is the most common intrusive rock in Earth's continental crust. It is familiar as a mottled pink, white, gray, and black ornamental stone. It is coarse- to medium-grained. Its three main minerals are feldspar, quartz, and mica, which occur as silvery muscovite or dark biotite or both. Of these minerals, feldspar predominates, and quartz usually accounts for more than 10 percent. The alkali are often pink, resulting in the pink granite often used as a decorative stone. Granite crystallizes from silica-rich magmas that are miles deep in Earth's crust. Many mineral deposits form near crystallizing granite bodies from the hydrothermal solutions that such bodies release.

- **Name origin:** The name appeared for the first time in works of the English botanists, physician and philosopher Caesalpinus in the 16th century.
- **Group:** Plutonic.
- **Colour:** Pink-grey.
- **Structure:** Massive, confining.
- **Texture:** Phaneritic (medium to coarse grained), holocrystalline, pan-hypidiomorphically grained, porphyric in places.

FIG:GRANITE CAP STONE

Granite captone in brihadeeshwara temple:

The Brihadeeshwara temple is one of the finest granite temples in the world. Granite is one of the hardest stones and the hardness falls between 6 and 8 on the Mohs scale. As the source of the granite used for the construction of Brihadeeshwara temple is unknown, the specific gravity of Indian granite was taken as 2.6 for the purpose of analysis (IS2003). The granite capstone occupies an area of 7.77 sq. m. (Vasudevan, 2003). The capstone was assumed to have been dragged to the top of the Vimana by means of elephants, using strong cables and wooden rollers, over the designed ramp 2003). The granite capstone occupies an area of 7.77 sq. m. (Vasudevan, 2003). The capstone was assumed to have been dragged to the top of the Vimana by means of elephants, using strong cables and wooden rollers, over the designed ramp

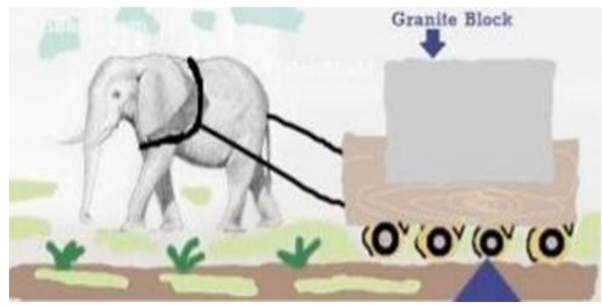
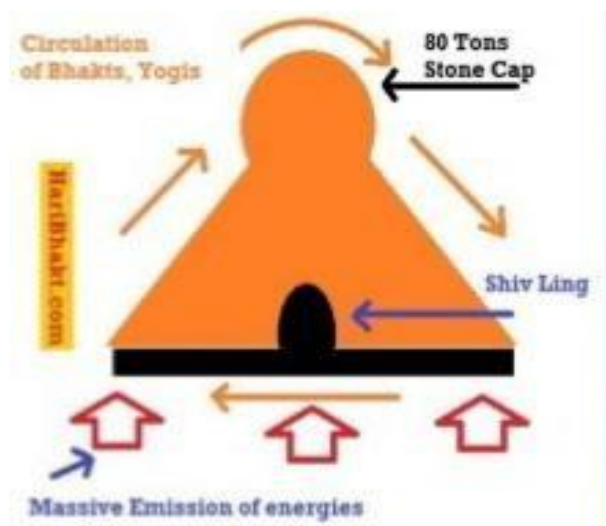


FIG :granite block stone



ABOUT BRIHADEESHWARA TEMPLE :

- Over 1000 elephants were working day/night, this popular theory by western investigators is that a 11km long incline plane was built, and the stone was rolled to the top on logs by elephants. The starting of the incline plane has been found and is called scaffold pit.
- A thick round brick wall 5 to 6 feet wide scaffolding around gopuram big stones are kept

sand is poured in the gap scaffolding spiral casing.

- Block and big stones are placed on the scaffolding and re moved with lesser energy than the previous method, breaking of egg shell opening of scaffolding.
- Scaffolding comes off, sand spills out, Vimna (temple tower) revealed, any mistake in levels will show up, plumb line perfect.

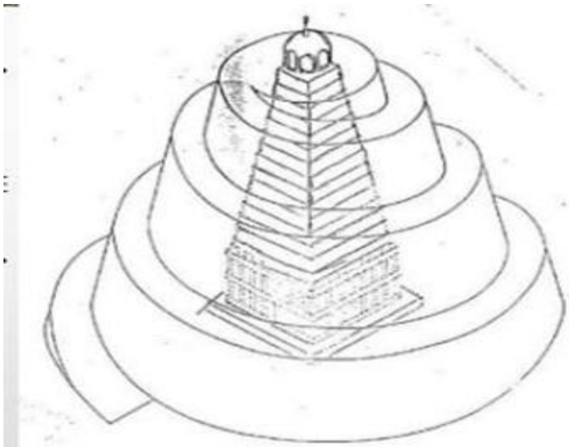


FIG: scaffolding construction

III. RAMPDETAILS

The ramp was assumed to be created using a local soil as it is temporary structure.The soil was assumed to have a cohesion of 26.33kpa, angle of internal friction of 33 degree and saturated unit weight 17kn\m3 based on literature studies (KANIMOZHI AND PANNEERSELVAM 2011)

Ramp system proposed for lifting the capstone weighting 80 tones(a) three dimenssional respresentation of the proposed ramp system (b) plan top view of ramp system (c)side view of ramp system(d) front view of ramp system.

Height of the temple before the placement of capstone and the kalasha was taken as 61 m, to the top of which the temporary ramp was built. The ramp system consisted of three slopes that need to be stabilized separately under the influence of the applied load. One was the main slope which was the longest, along which the load moved upwards. The second was the side slope constructed for supporting the main slope. The third one was the back slope, behind the ramp and the temple, supporting the last part of the side slope. The side and main slopes were assumed to be made of local. Ramp system proposed for lifting the capstone weighing 80 tons: (a) Three-dimensional representation of the proposed ramp system (b) Plan/Top view of the. mp system (c) Side view of the ramp system (d) Front view of the ramp system.

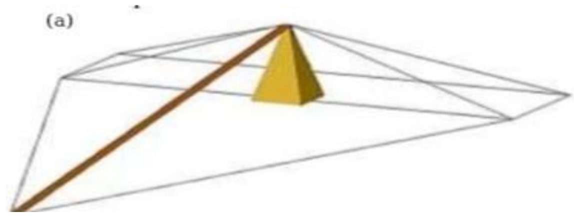


Fig: Three dimension plan

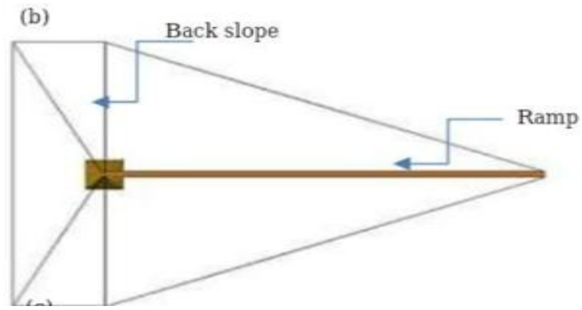


Fig: Two dimension plan

IV. STABILITY ANALYSIS:

The slope stability analysis was carried out using SLOPE/W (Geostudio, 2012) software package. The limit equilibrium technique was adopted for the analysis, based on the Morgenstern-Price Method (Morgenstern and Price, 1965). The Morgenstern-Price method calculates the factor of safety considering the equilibrium of forces as well as the moments of the slope system. The shear and horizontal components of interslice forces are considered in this method which can be represented by an appropriate function. The interslice shear force is represented by the equation 1 $X= E * ł * f(X)$

where X is the shear component of interslice force, E is the horizontal component of interslice force, f(x) is the function for interslice force and (ł } is the percentage of the function used. In the present study, the half-sine function was adopted. A circular slip surface was assumed. The trial slip surfaces were considered by specifying the entry and exit points for the slip surface.

Slopes were drawn as regions and the material properties were assigned in SLOPE/W. The soil was assumed to follow the Mohr-Coulomb criteria of shear failure given by equation

(2). tf=C'+~' *tanØ'.

where tf is shear stress at failure, C' is effective cohesion coefficient, ~'=~-Uw is the effective normal stress and Ø is the effective angle of internal friction. The conventional analysis in SLOPE/W considers fully saturated soil as the critical condition, therefore the soil pores are filled with water alone and the uw is the pressure due to this water in the pores. The pore water pressure is compressive in nature in case of saturated soils. However, in the normal scenario soil need not be fully saturated. Unsaturated soils can be considered as multi- phased systems (soil, water and air being the most common combination of phases in nature). In such cases due to the interface effect the pore water pressure is negative. Thus, the value (Ua-Uw), called suction needs to be considered, where is the pore air pressure.

Suction increases the shear strength and factor of safety significantly. The pore air pressure is an important state variable in the shear strength equation for unsaturated soils. The Extended Mohr Coulomb Criteria (Gofar and Rahardjo, 2017) is commonly for calculating the shear strength of unsaturated soil which is shown in equation (3)

Tf=C'+(~- Ua)tanØ'+(Ua-Uw)tanØþ.)

Where Ua-Uw is the matric suction at failure and Øþ is the angle of internal friction with respect to matric suction at failure, which are elaborated in figure 3. The is taken as zero in case of conventional SLOPE/W analysis. can be taken up to 0.5 times Øþ'.

Therefore, in the study was considered as 15 degrees. The suction value was arbitrarily taken as 100 kPa, creating a negative pressure head of 10 m, which was applied as a spatial function. The horizontal and vertical coefficients of seismic load were considered as 0.16 and

0.04 respectively (IS: Part 1, 2002) since the temple location belongs to zone-3 and few earthquakes were reported before. ices are verified with respect to the force polygon. Different sections were considered on the main slope to find out the most critical placement of the load.

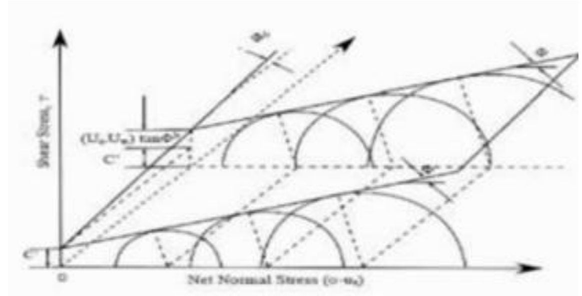
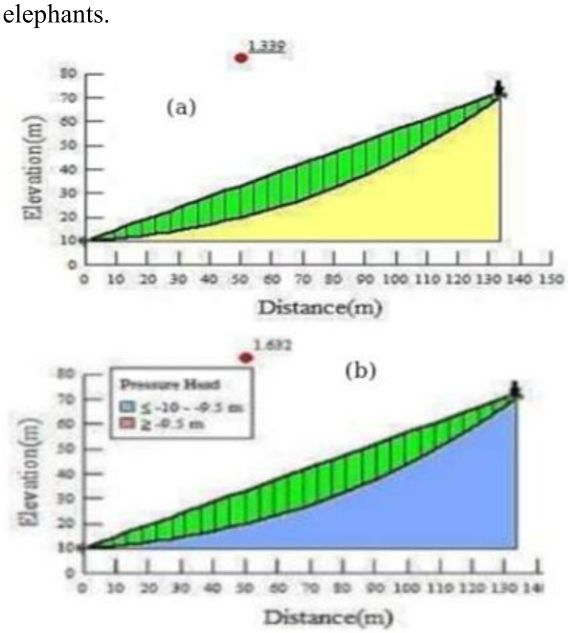
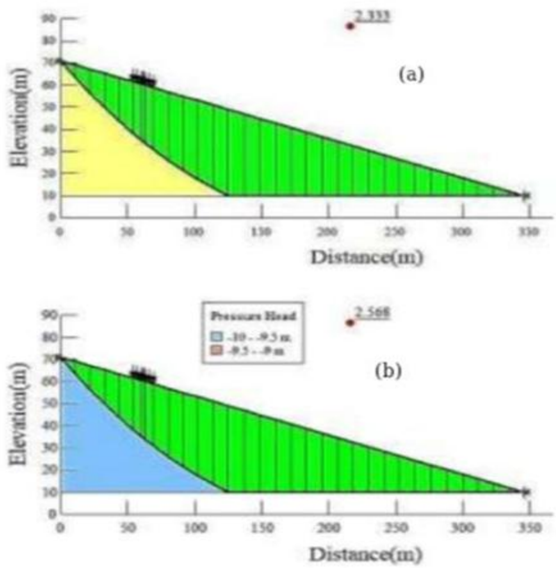


Fig 3. Extended Mohr-Coulomb Failure Criteria

V. LOADING MECHANISAM

The load acting on the ramp consisted of granite capstone, elephants, cables, wooden rollers, and human workers. The capstone was assumed to be of dimension 2.788 m × 2.788 m and weighing 80 tons. The elephants and others were assumed to create a load of 15 tons. Elephants were considered to be of 6.5 m in length. Leg to leg distance for an elephant was taken as 1.5 m. As such the load was considered to extend for an overall length of 16 m. The mechanism of moving the capstone was assumed to have involved elephants dragging the cabled stone, placed over smooth rollers made out of strong cylindrical wood. One elephant successively rearranged the wooden rollers underneath the load according to the ascent of the capstone. The inclination of the ramp is kept sufficiently low (10 degrees) to allow comfortable movement of the elephants.





VI RESULTS AND DISCUSSION

For analysis, the slope geometry was created in SLOPE/W and the material properties and surcharge load density were assigned. Entry and exit points for slip surfaces were specified and the dynamic coefficients were given as inputs.

The slopes were analyzed in both saturated and unsaturated conditions. During analysis, it was also noticed that the factor of safety for the localized failure of the slope is less critical compared to the case with the entry and exit points of slip surface are at either end of the slope. Section 1 was considered at the starting point of the slope. Section 2 was considered at a horizontal distance of 70 m away from the first section. Sections 3 and 4, 70 m apart, gave same factor of safety values for the saturated condition. Section 4 gave a better factor of safety in case of unsaturated analysis. It was noted that the factor of safety values suddenly decreased in section 5 as shown.

Therefore, in order to locate the critical placement of load more precisely, two more sections were considered between section 5 and the temple. It can be seen from Table 1 that the factor of safety continued to decrease and gave the least value in saturated and unsaturated conditions when the load was placed at section 7 as shown in figure 5. It was observed that, considering an unsaturated condition has caused an increment of approximately 10 percent in the factor of safety of slope in all the cases discussed above.

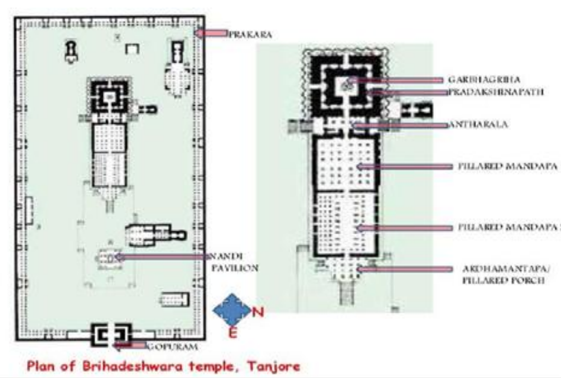
Factor of safety analysis for side slope with side elevation 61 m (a) Critical slip surface in saturated condition (b) Critical slip surface in unsaturated condition The side slope was analyzed at two sections, one at 61 m side elevation (figure 6) and one at 30.5 m side elevation (figure 7).

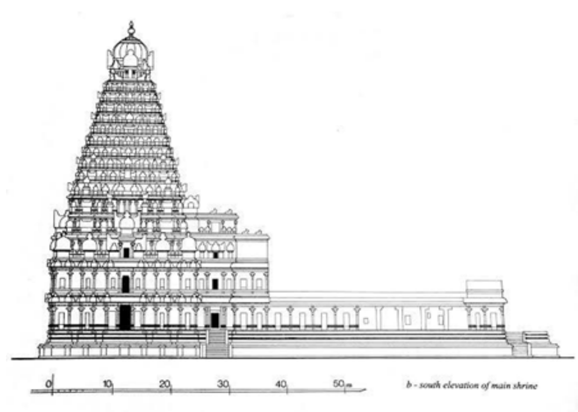
The side slope, supporting the main slope was provided at a uniform inclination of 25 degrees throughout, which was much higher than the main slope, as the elephants do not move directly on this slope. Thus, the side slope was more critical than the main slope. Table 2 gives details of the analysis of side slope.

Table 2. Factor of safety values for side slope

Section	1	2
Height(m)	61	30.5
Horizontal extend(m)	131	65.4
Distance of section from temple(m)	0	173
Factor of safety for critical slip surface (Saturated)	1.339	1.557
Factor of safety for critical slip surface(unsaturated)	1.632	2.074

STRUCTURAL PLAN AND ELEVATION





ELEVATION OF TEMPLE.

VII CONCLUSION

In the present study, a ramp was assumed to be made out of local soil and was analyzed for failure under saturated and unsaturated conditions using SLOPE/W. The ramp extended from the top of the Vimana to a horizontal distance of 346 m and was supported by uniformly inclined side slopes and a back slope.

The granite capstone of 80 tons was considered to be dragged by elephants to the top of the Vimana. An inclination of 10 degrees for the main slope and 25 degrees for the side-slope was observed to be safe for both saturated and unsaturated conditions. The minimum factor of safety for the main slope was observed when the load extended 16 m from the top of the Vimana, for both unsaturated and saturated conditions.

For the side slope, the lowest factor of safety was observed for the section which had a height of 61 m from the ground surface, for similar soil conditions. Even though the load was not moving directly over the side slope, the side slope was observed to be more critical in comparison to the main slope of the ramp, reason being a larger angle or inclination value in comparison to the main slope.

The present study primarily focused on only one of the possible ways of carrying the capstone to the top of the Vimana. However, further studies need to be conducted to explore other possible methodologies.

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